

OPTICAL LOW COHERENCE REFLECTOMETRY APPLICATIONS TO MEAT TENDERNESS TESTING

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EXECUTIVE SUMMARY

The goal of this research project is to develop an optical low coherence reflectometry (OLCR) system for use in testing meat tenderness. This system will use a precision reflectometer that sends out infrared light to a sample and collects the reflections from the outer layers of the meat to plot a structural representation of the sample in a reflectivity-over-distance measurement. Tenderness is correlated to the relative densities of proteins and connective tissues in the meat, which this technique may be able to image. In the winter of 2007, a system was constructed for testing purposes. In the spring of 2007, testing and data analysis procedures were developed and tests were run on a group of meat samples of varying tenderness to see if correlations could be established between results from OLCR testing and shear force testing. The results show preliminary relationships between tenderness and beam attenuation into the meat samples. Future research is required to have a statistically significant experiment. Modifications to the testing procedure and data analysis techniques are required to establish better correlations.

INTRODUCTION

The most effective current method of measuring meat tenderness involves shear force testing. This testing requires the meat to be cored, cooked, and then cut with a blade of specified dullness. The force that is required to shear the meat is to be measured. With this process, it can be determined how tender the meat is, which is correlated to the ease with which it can be chewed and how palatable it will be. Figure 1 shows a picture of a set of New York Strip steaks being cooked in preparation for measurement of meat tenderness using established techniques. Figure 2 shows a picture of several steaks that have been cooked to specification and are ready for sheer force testing. Figure 3 shows a picture of the shear force instrument that is the present standard for measuring meat tenderness.



Figure 1: A Cal Poly graduate student cooking several New York Strip steaks in a controlled manner in preparation for a meat tenderness measurement. The internal temperature of the steak is monitored to maintain consistency in cooking conditions.

Meat tenderness testing is very important to the meat industry, as people are willing to spend more money on meat that is tender versus not tender. Shear force testing, though accurate, is time consuming, damaging to the meat, and reduces the total amount of meat available for sale.



Figure 2: Several different cuts of beef have been cooked to specification and are ready to go to the calibrated shear force testing station to determine their tenderness rating. This is the traditional process for measuring tenderness.

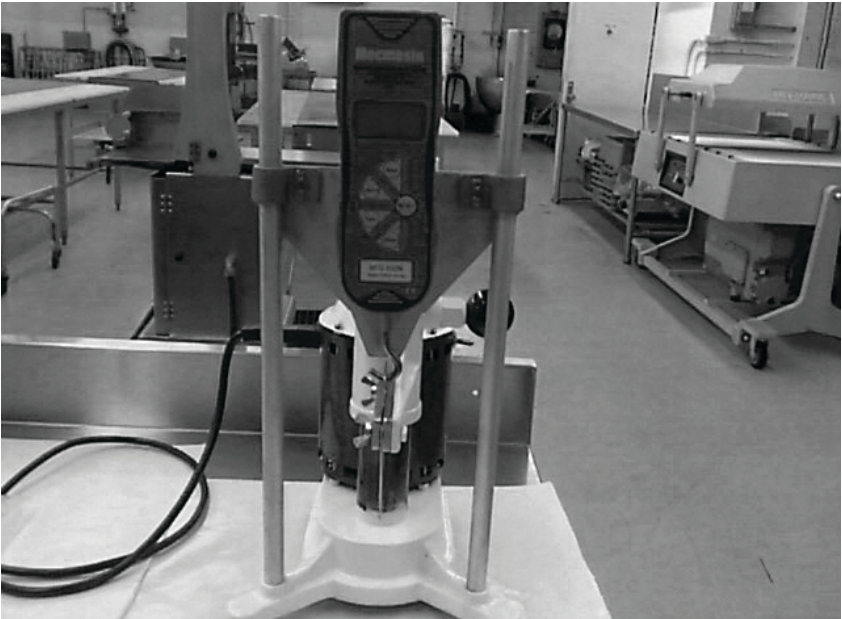


Figure 3: The calibrated shear force measurement instrument. A core from the cooked steak is clamped into a holder. The force that a cutting blade needs to cut the meat is then recorded.

The purpose of this research project is to investigate the application of a technique known as OLCR as an effective and noninvasive means of determining the tenderness of meat. Optical low coherence reflectometry is a measurement method that studies the interference patterns of reflected waves

compared to reference reflections in order to determine the reflectivity characteristics of the sample under test. This project arose from a search for a better way to test the tenderness of meat by Professor John Beckett of the Cal Poly Agriculture Department and the search for applications of a reflectometry process by Professor Dennis Derickson of the Electrical Engineering Department. This proposed solution will correlate the reflection pattern of a sample of meat to its tenderness.

The first phase of the project was to assemble a measurement system capable of measuring the reflectivity versus distance into beef steak samples. In order to accomplish this, a reflectometry system needed to be assembled for meat tenderness analysis. An Agilent 8504B Precision Reflectometer located in the Electrical Engineering Department's Photonics lab was used as the measurement engine in the study. This instrument was donated to the EE department by Agilent Technologies. The 8504B is capable of measuring reflectivity as a function of distance with 15 micron (in air) resolution and 80 dB of round trip path loss in the sample. A custom optical interface had to be developed in order to couple the probing light beam to the sample under test. A lensing system was assembled for the reflectometer using a Graded Index (GRIN) lens. A computer to instrument control interface was designed using the LabView programming environment in order to automate the measurement. Baseline measurement performance for the measurement samples was then obtained.

The second phase of the project was to compare measurements using the reflectometry system to measurements made by the traditional cook and shear method. The optical testing process was refined and a group of meat samples was tested and the data processed. The next section of this report will present a description of the factors that determine the tenderness of meat and provide a more detailed overview of the reflectometry process used in the experiment. Finally, the testing phase of the project will be described, the results will be presented, and suggestions will be made for future measurements to assess correlation of the two measurement methods.

BACKGROUND

Cuts of meat are cross-sections of a cow's skeletal muscle. Skeletal muscle is one of three types of muscle that cows and other animals have. Most common muscles, such as the biceps or hamstring, are skeletal muscles. Skeletal muscles are long, narrow tissues composed of many cells running the length of any given muscle. These cells, also known as muscle fibers, are organized into small bundles known as fascicles. These bundles are illustrated in Figure 4. Fascicles are the smallest physical grouping of muscle cells. A bundle of fascicles composes the muscle as a whole. In the macroscopic structure of a muscle, there exists a large number of fascicles, each surrounded by a layer of connective tissue. Connective tissue forms a significant part of the muscle structure and joins in with surrounding muscle cells and fascicles by adipose tissue, which is primarily fat and blood vessels.

Structure of a Skeletal Muscle

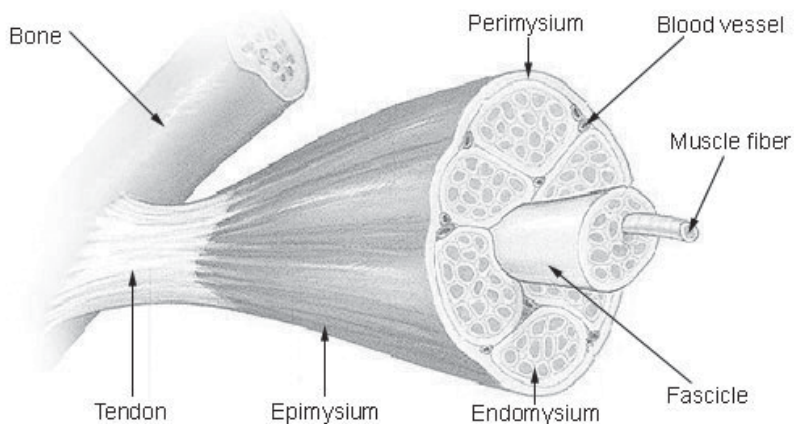


Figure 4: An illustration of a skeletal muscle.

Studies have shown that higher concentrations of proteins and connective tissues can contribute to less tender meat. Further testing may be able to show if this relation is true and if it can be found using the reflectometry technique of this project.

A noninvasive method of testing meat tenderness that exists currently is one that correlates the color of meat at a specified amount of time post

mortem and exposure to air to tenderness. A reasonable relation between the color and tenderness is found with this technique. However, it is not as reliable as shear force testing and it would be very desirable for a more reliable noninvasive technique to be developed. Because of this, a multitude of other methods of testing meat tenderness have been and are being explored. However, very few of them show any promise, which is where the technique of OLCR comes in.

The backbone of the OLCR technique used in this project is the Agilent 8504B Precision Reflectometer. Its operation is based on a Michelson Interferometer in which a beam of light is split with part of it going to a fixed mirror and the other to a moving mirror. After the beams are reflected back, they are recombined and the beam from the fixed mirror is analyzed with respect to that of the moving mirror using interference pattern analysis. Figure 5 shows the block diagram of the reflectometry system that was used.

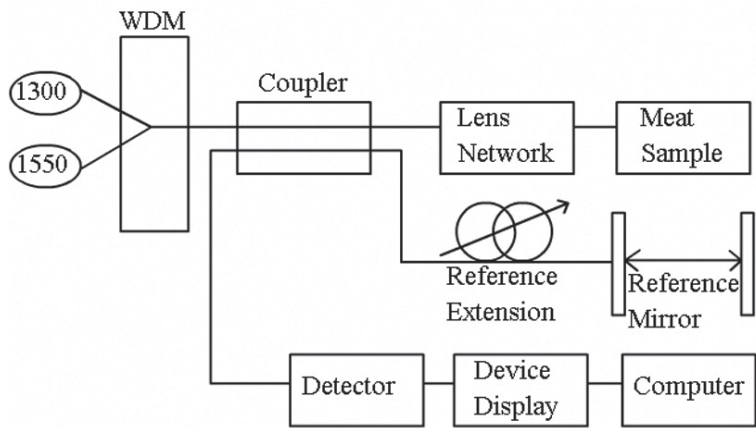


Figure 5: The block diagram of the optical low coherence reflectometry system used for the reflectivity versus distance measurement. Optical interference at the detector occurs when the spacing from the coupler to the meat sample equals the spacing from the coupler to the reference mirror. The wide spectral width of the source makes the interference pattern quickly fade away when two paths differ by more than 15 microns.

A wavelength division multiplexer selects either the 1550 nanometer or 1300 nanometer wavelength infrared LED light source and sends it to the coupler. The coupler splits this light and sends half of it to the reference cable and the other to the test cable. The test cable comes out of the machine and

connects to a lens network. The length of the reference cable is set so that it is equal to the length of the test cable plus the lens network. When the distance from the coupler to a reflection in the meat sample is equal to the distance between the coupler and the reference mirror, an interference signal appears in the detector. When these two distances are more than 15 microns apart, the interference signal vanishes. This 15 micron distance resolution is controlled by the spectral width of the optical signal emitted by the LED source. Reference 1 provides a detailed description of the instrument's operation.

A lens interface to the sample was designed as part of the project. Figure 6 shows that the assembly consists of a pigtail ferrule feeding a GRIN lens in a lens tube.

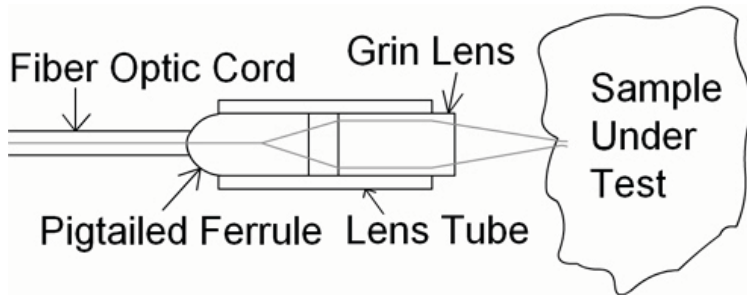


Figure 6: The optical assembly that was used to couple light from the 8504B measurement instrument into the meat sample under test. The fiber ferrule terminates the fiber with an 8 degree cleave angle and an antireflection (AR) coating. The cleave and the AR coating reduce the residual reflectivity signal back into the instrument. A 0.23 pitch AR coated GRIN lens was then used to produce a converging beam into the sample. The ferrule to GRIN lens spacing was adjusted to achieve the correct convergence angle of the beam for this measurement. Using Gaussian beam analysis theory, the converging beam was designed to have a working distance of about 3 mm near its minimum beam waist. The diameter of the beam was about 20 micron at the beam waist.

Figure 7 shows a picture of the measurement system that was assembled in the project. Figure 8 shows a close up of a sample being measured.

DESIGN

The original budget for the project was \$5000 (\$3800 of that going towards purchasing parts). As can be seen in Figure 6, the set-up consists of the reflectometer, lens assembly, and computer interface. The reflectometer itself costs \$50,000; however, this device was already in the Electrical Engineer-



Figure 7: The Optical Coherence Tomography test setup. The Agilent 8504 instrument at the top of the picture provides the reflectivity-versus-distance measurement. The XYZ stage and the imaging lens are shown above a meat sample at the bottom of the picture.

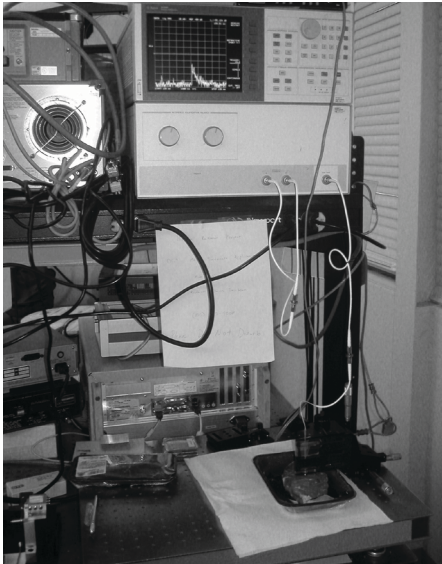


Figure 8: A close up of the GRaded INdex (GRIN) lens assembly that was used to measure the reflectivity versus distance into the meat sample. The average measurement depth of penetration was about 1.2 mm assuming an index of refraction of 1.5.

ing photonics lab. Also, several parts used in the project, such as the fiber optic cable and miscellaneous mounting equipment, were not purchased specifically for this system and will not be attributed to the cost. Phases one and two of the project occurred in the winter quarter of 2007 and the third phase in spring of 2007. In this first phase of the project, the computer interface was programmed so that a data trace could be taken from the device and sent to the computer for analysis. To present the plot, the points are exported to Excel for compiling and analysis. Coding to analyze the plots was not added until later. Getting familiar with the LabView graphical programming environment, developing the code, and testing it took three weeks. During this time, work was also being done on the second phase of the project and continued through the end of the quarter. The second phase of the project entailed assembling the mechanical parts of the system, including the lens network, imaging station, and fiber optic cables. An x-y-z posi-

tioning system and a mounting board were purchased (\$906) for holding the lens system. A Grin lens was decided upon for ease of use and the ability to modify the focusing distance by changing the distance between the ferrule and lens. The entire lens system cost \$132. The lens parts were ordered in the middle of the quarter but took several weeks to be obtained. In order to get the reference cable the same length as the test cable plus the lens system, all of the parts were measured and it was decided to splice the needed length of fiber optic cable to the lens system. Splicing a cable requires a procedure known as fusion splicing. Each of the cables were to be cut back and stripped so that only the thin fiber was exposed and then sheared to give an even surface on the ends of either fiber for splicing. The splicing was then done with a fusion splicer that used automated aligning procedures to exactly align the fibers, pre-fusion electrical pulses to blow off dust and clean the fibers, and finally high voltage to melt the fibers and fuse them together. The fusion splicer estimated the finished splice loss at 0.12 decibels. Once the fiber connected to the pigtailed ferrule was fused to the test cable, the ferrule was inserted into the lens tube with the Grin lens (as seen in Figure 2) and the lens system was ready for testing. Being in the spring, the testing phase of the project began. Another LabView program was coded so that the plots in Excel could be imported into LabView for analysis. Also, during this phase of the project, tests were performed on meat samples and this will be discussed in the methods section of the report.

METHODS

Different tests were performed on the lens assembly to ensure functionality before scanning. First, an infrared detector card was used to see if any light was coming out. When the infrared light coming from the lens system hit the card, it lit up and was visible. The next test performed was with an optical power meter that works by measuring the power generated from a small InGaAs photodetector. Before the fuse, 21 W of power was recorded coming from the fiber and after the fuse, 20 W of power was detected coming out of the pigtailed ferrule. In order to calibrate and fine tune the focusing distance between the lens and sample, several sweeps were performed until the reflec-

tivity of the sample could be maximized when the sample was a specified distance away. Figures 9 and 10 are examples of plots that were generated from this test.

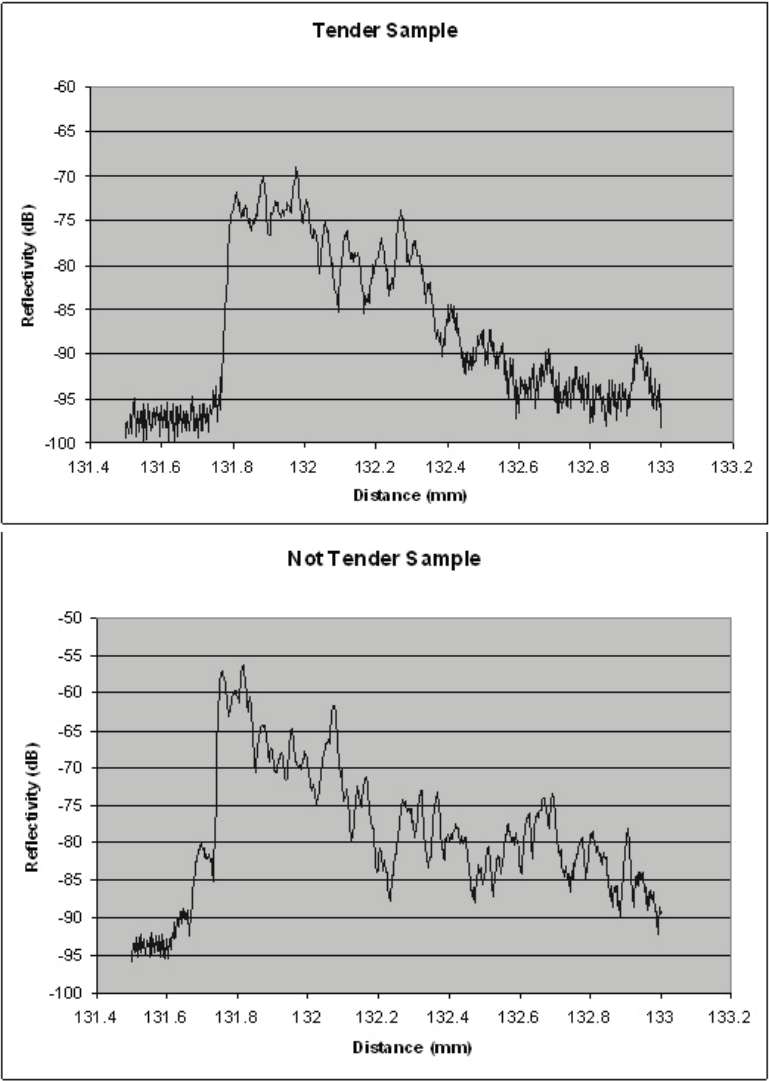


Figure 9: (top) An example reflectivity measurement for a tender meat sample.
Figure 10: (bottom) An example of the reflectivity versus distance from a meat sample that was considered not to be tender.

For the testing phase of the project, ten meat samples of varying tenderness were obtained from the Cal Poly Agriculture Department. The following cuts were in the test group: 2 top sirloin, 3 eye of the round, 4 New York strip, and 1 bottom round. First, they were analyzed with the OLCR testing system in the EE Photonics Lab and then sent back to the Agriculture Department to obtain shear force testing results. When being tested by the OLCR system, 5 to 8 traces were taken from each piece of meat at different points. At each point the scanning range and point were selected to maximum the first reflection peak and display most of the region of reflection as seen in Figures 9 and 10. Each point had sixty-four data traces averaged to eliminate nonrecurring reflections and noise.

The task was then to identify key features of the reflectometry trace that might correlate to meat tenderness. A series of different analysis techniques were performed on the data traces, but the only ones that showed real promise were the penetration depth of the beam into the meat that could be imaged and the decay slope of the reflections due to the attenuation of the beam into the meat. These two also offer similar trend lines as they are measuring related features and the results are discussed in the results section.

RESULTS

All of the plots generated in the testing phase of the project were analyzed in Excel and LabView to search for correlations with the tenderness testing results from shear force testing and reasonable correlations were found with penetration depth and decay slope. Figures 11 and 12 show these relationships. From mid to high tenderness values, there is a correlation between tenderness and both penetration depth and decay slope. In other words, tender samples have a shallower penetration depth for the 1.3m infrared light. This trend did not hold for the samples that were the least tender. It seems after a point, penetration depth maximizes and meat being less tender will actually decrease the penetration depth of the beam. We are as of yet uncertain what could be causing this. As for why penetration depth is affected by tenderness, it is known that the main structures in meat are proteins and different fibers which contribute to tenderness. Considerable work is left in making a

more sound judgment on the correlation of reflectometry measurements to meat tenderness.

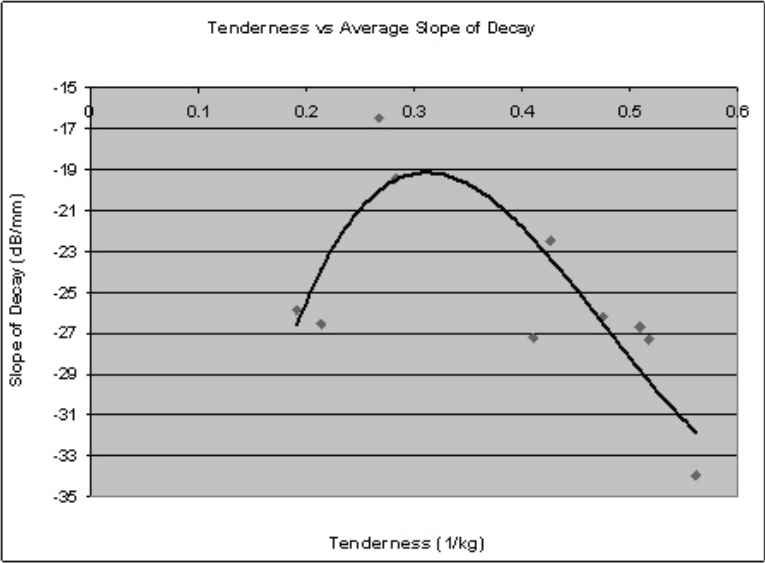


Figure 11: Here the slope of the reflectometry measurement in dB/mm is compared to the classical meat tenderness measurement on the horizontal axis. The horizontal tenderness axis is in units of kg-1. This means that a very tender sample is to the right and less tender is to the left.

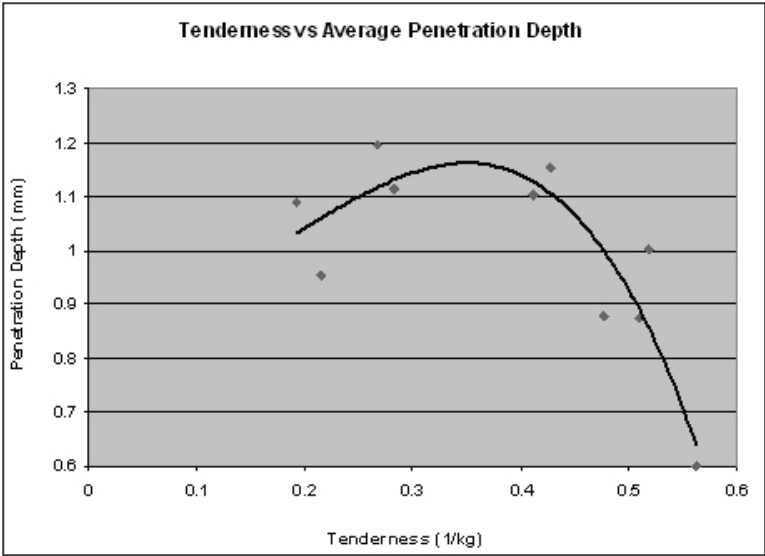


Figure 12: In this assessment, the depth of penetration into the sample is compared to the tenderness of the sample.

CONCLUSIONS

There are several factors related to tenderness that can be addressed with the reflectometry technique. The most promising factors in terms of determining the tenderness of meat are connective tissue and protein densities. The more connective tissue present in the muscle and the denser the proteins in the myofibrils, the less tender meat is. These two factors have a significant effect on the reflectometry readings. The decay of the waveforms as imaging is done into the beef is a good indicator of protein and tissue densities. For future research with this device, the data acquisition technique should be more standardized so that all data traces are obtained from the exact same sequences and the results are more meaningful. A much larger sample size is also required to further examine correlations between the present standard and this proposed measurement procedure. Also, a senior project is underway that will add automated actuators to the x-y-z positioning system so that a sample may be imaged at several positions and by combining the data from several positions a three-dimensional image of the beef can be created. With future progress, OLCR may develop into an effective means of determining meat tenderness that can be used for commercial implementation.

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